PREDICTION OF THE ADDED RESISTANCE OF A SWATH SHIP

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It was reported[1,2,3] that for various SWATH models, in the supercritical zone, as the wave height increases, the resistance decreases dramatically (up to as much as 24% of the calm water resistance) over part of the speed range. Indeed, this result is very significant in the application of SWATHs to ship operations where speed loss is of prime importance. In order to clarify this phenomenon, a theoretical investigation of 1st and 2nd order wave effects based on a 3-D panel source distribution technique has been conducted and some results are reported here.

1. Method to Approach to the Problem

In general, there are two methods of solving the added resistance of vessels travelling in regular waves (or drifting force when the vessel is in stationary); the far and near field approaches. The far field approach derives the added resistance from consideration of conservation of either the total energy or the total momentum of the fluid. This method requires a knowledge of the total velocity potential and its derivatives far away from the vehicle. In contrast, the near field approach calculates the added force from the direct integration of the pressure on the wetted surface of the vessel. Both methods have advantages and disadvantages over the other. The near field approach requires more computational efforts and is more unstable numerically compared to the far field. However, the vertical component of the drifting force can be examined with the near field approach. For the present study, the near field approach has been chosen.

In order to define the motions of a body travelling in waves, two sets of reference systems are employed. The first is the inertial axes system 0-xyz advancing in space with steady speed U, with x pointing towards the advancing direction, y towards port and z pointing upwards. The origin of this system is in the plane of the undisturbed free surface. The other axes system 0x'y'z' is fixed to the body. The two systems coincide with each other when there is no motion. For any point on the hull surface with position vector $\vec{r}'$ in the body fixed system, its displacement from the at rest position in the inertial frame can be expressed as:

$$\vec{\alpha} \cong \vec{\xi} + R_1\vec{r}' + R_2\vec{r}' + 0(\varepsilon^3) \tag{1}$$

where $\vec{\xi}$ is the translational motion vector consisting of surge(ξ_1), sway(ξ_2) and heave(ξ_3), and R_1 and R_2 are the transformation matrices due to the rotation of the body:

$$R_1 = \begin{bmatrix} 1 & \xi_6 & -\xi_5 \\ -\xi_6 & 1 & \xi_4 \\ \xi_5 & -\xi_4 & 1 \end{bmatrix} \tag{2}$$

$$R_2 = \begin{bmatrix} -\frac{1}{2}\left(\xi_5^2 + \xi_6^2\right) & 0 & 0 \\ \xi_4\xi_5 & -\frac{1}{2}\left(\xi_4^2 + \xi_6^2\right) & 0 \\ \xi_4\xi_6 & \xi_5\xi_6 & -\frac{1}{2}\left(\xi_4^2 + \xi_5^2\right) \end{bmatrix} \tag{3}$$

where ξ_4, ξ_5 and ξ_6 are roll, pitch and yaw motions, respectively.

By assuming an inviscid, irrotational and incompressible fluid, the problem is confined to solving a governing equation (Laplace's equation) which satisfies boundary conditions and an appropriate radiation condition which makes the solution unique. For the problem of a vessel travelling in waves, assuming that the forward motion is small and the frequency of oscillation is high, a simplified free surface boundary condition can be used[4]:

$$-\omega_e^2\phi + g\frac{\partial\phi}{\partial z} = 0 \qquad \text{on } z = 0 \tag{4}$$

which corresponds to the zero speed free surface boundary condition if the encounter frequency (ω_e) is replaced by the wave frequency. The speed dependent potentials can be calculated as follows;

$$\phi_j = \phi_j^0 \qquad \text{for } j = 1, 2, 3, 4$$

$$\begin{Bmatrix}\phi_5\\ \phi_6\end{Bmatrix} = \begin{Bmatrix}\phi_5^0\\ \phi_6^0\end{Bmatrix} \pm \frac{U}{i\omega_e}\begin{Bmatrix}\phi_3^0\\ \phi_2^0\end{Bmatrix} \tag{5}$$

where ϕ_j^0 are speed independent velocity potentials and j=1 denotes a surge motion, j=2 for sway, j=3 for heave, j=4 for roll, j=5 for pitch and j=6 for yaw.

The fluid pressure is given by the unsteady Bernoulli's equation,

$$P = -\rho[\, gz + \frac{1}{2}(\nabla\phi)^2 + (\frac{\partial}{\partial t} - U\frac{\partial}{\partial x})\,\phi] \tag{6}$$

and the fluid force acting on the wetted surface is given by:

$$\vec{F} = \int_S P\vec{n}\, ds \tag{7}$$

where the normal vector $\vec{n}$ directs inwards to the body surface.

Expanding pressure and force as a perturbation expansion series, the forces of zero order to higher order, as desired, can be calculated by collecting terms of the same order:

$$\vec{F}^{(0)} = \int_{S_0} P^{(0)}\vec{n}^{(0)} ds \tag{8}$$

$$\vec{F}^{(1)} = \int_{S_0} P^{(1)}\vec{n}^{(0)} ds + \int_{S_0} P^{(0)}\vec{n}^{(1)} ds + \int_{S_1} P^{(0)}\vec{n}^{(0)} ds \tag{9}$$

$$\vec{F}^{(2)} = \int_{S_0} P^{(2)}\vec{n}^{(0)} ds + \int_{S_0} P^{(1)}\vec{n}^{(1)} ds + \int_{S_0} P^{(0)}\vec{n}^{(2)} ds + \int_{S_1} P^{(1)}\vec{n}^{(0)} ds + \int_{S_1} P^{(0)}\vec{n}^{(1)} ds + \int_{S_2} P^{(0)}\vec{n}^{(0)} ds \tag{10}$$

The zeroth order force is the hydrostatic force due to the buoyancy of a floating structure. The first order force is the hydrodynamic force due to the motion of the structure. The second order force contributes to the drifting of the floating structure in the stationary mode (drifting force) or to the increase in the resistance of the travelling vessel in waves (added resistance).

After some manipulation, the mean second order force can be written [5] :

$$\vec{F}^{(2)} = \frac{1}{4}\rho g \int_{L_0} |\zeta_r|\,\vec{n}_2 dl - \frac{1}{4}\rho \int_{S_0} |\nabla\tilde{\phi}|^2 \vec{n}^{(0)} ds + \frac{1}{2}\mathrm{Re}\{\tilde{R}_1^* \tilde{\vec{F}}^{(1)}\}$$
$$- \frac{1}{2}\rho\omega \int_{S_0} \mathrm{Im}\{\tilde{\vec{\alpha}}^* \nabla\tilde{\phi}^{(1)}\}\vec{n}^{(0)} ds + \frac{1}{2}\rho U \int_{S_0} \mathrm{Re}\{\tilde{\vec{\alpha}}^{(1)*} \nabla\tilde{\phi}_x^{(1)}\}\vec{n}^{(0)} ds$$
$$+ \frac{1}{2}\rho g A_w x_{c.f}\, \mathrm{Re}[\xi_4^* \xi_6]k \tag{11}$$

where the superscript ~ symbol denotes the complex amplitude of the variable, * the complex conjugate, A_w the water plane area and $x_{c.f}$ the x coordinate of the centre of flotation. The first order relative wave elevation due to the combined wave system and motion of the body is given by

$$\zeta_r^{(1)} = \zeta^{(1)} - \xi_3 - \xi_4 y + \xi_5 x \tag{12}$$

and to account for the actual surface length along the water line, the normal direction at the water line is modified as:

$$\vec{n}_2^{(0)} = \frac{(\vec{n}_1^{(0)}, \vec{n}_2^{(0)}, \vec{n}_3^{(0)})}{\sqrt{\vec{n}_1^{(0)2} + \vec{n}_2^{(0)2}}} \tag{13}$$

As seen in the above equation, the total 2nd order force consists of 6 terms, each having its own physical meaning. The first component represents the contribution from the changing wetted surface area due to the relative free surface elevation. The second component is the effect of the square of the velocity in Bernoulli's equation indicating a pressure drop around the wetted surface of the hull. The third term is the effect of the first order fluid force due to the rotation of the body axis. The fourth component represents the change of the pressure gradient field on the wetted surface due to the body motion. The fifth term is called a convective term due to the steady forward speed. The last term accounts for the second order motion effect in rotation of the axis on the vertical force which becomes zero in head seas.

3. Numerical Results

Figs. 1 to 4 show the calculated and measured added resistance coefficients of the SWATH1-C8 model (tandem strut, for geometry see Ref.[1]) against frequency at four speeds. In general, the agreement between the two are good, in particular, for the second set of higher waves. In Fig.3 at Fn=0.39, the negative added resistance increase can be seen for the first set of wave heights and virtually zero increase for the second set. The speed of Fn=0.39 is at the upper end of the range (Fn=0.31-0.39) where the negative added resistance increase occurs[1]. The theoretical prediction shows a resistance decrease near heave resonant frequency (also at Fn=0.52) and gives no resistance increase up to medium frequencies.

The theoretical predictions showed nearly zero resistance increase over the speed range, 0.31-0.39 where the large amount of resistance decrease (up to 24% of the calm water resistance) occurs as the wave height increases. Therefore, in conclusion, the present theory, based on the 3-D diffraction, supports the experimental finding to some extent but does not as yet provide an answer to the problem. Other possible theoretical investigations as mentioned in Refs.[1,2] are under way.

Acknowledgements

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References

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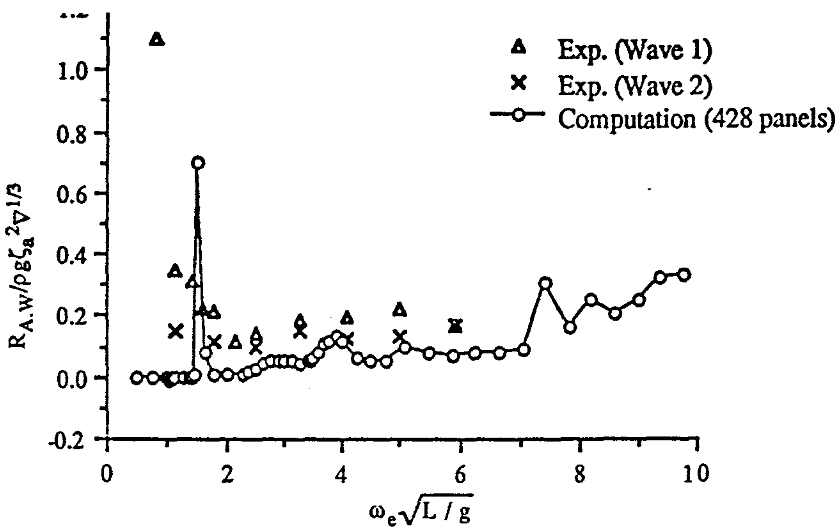
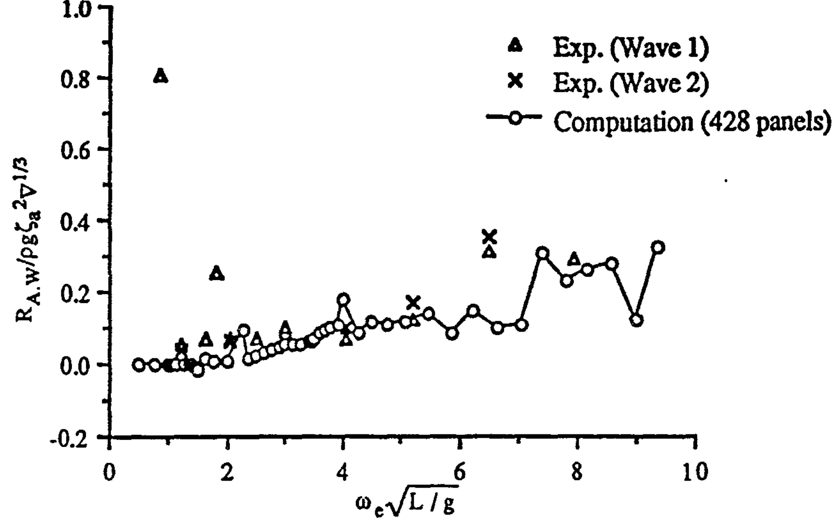


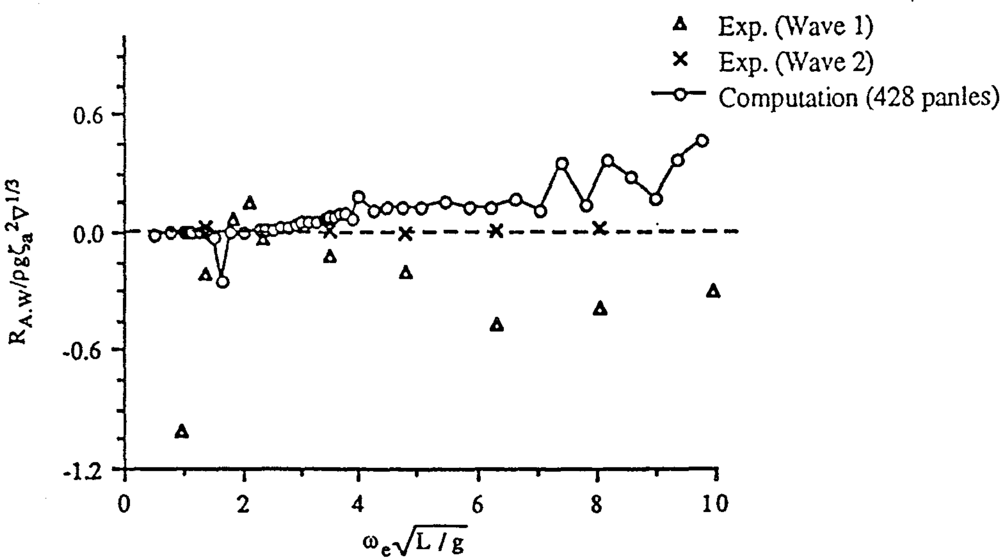
Added resistance coefficient vs non dimensional wave frequency of encounter for SWATH1-C8 at Fn=0.13

Fig.1



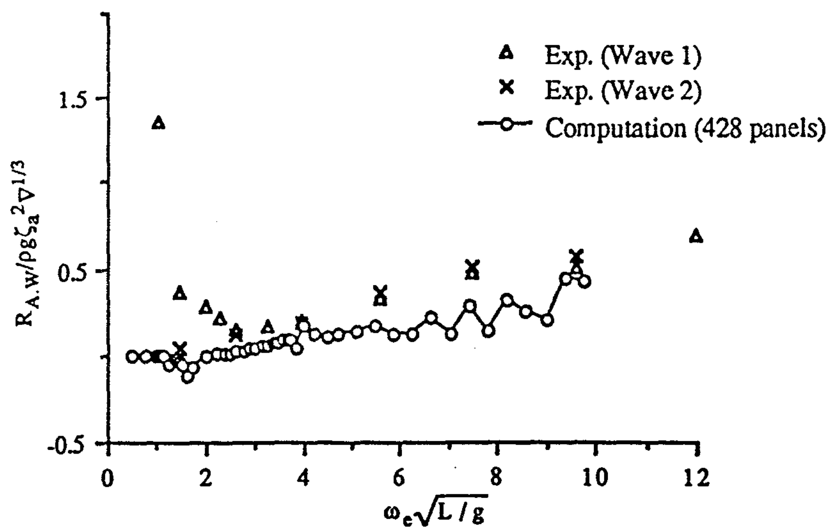
Added resistance coefficient vs non dimensional wave frequency of encounter for SWATH1-C8 at Fn=0.26

Fig.2



Added resistance coefficient vs non dimensional wave frequency of encounter for SWATH1-C8 at Fn=0.39

Fig.3



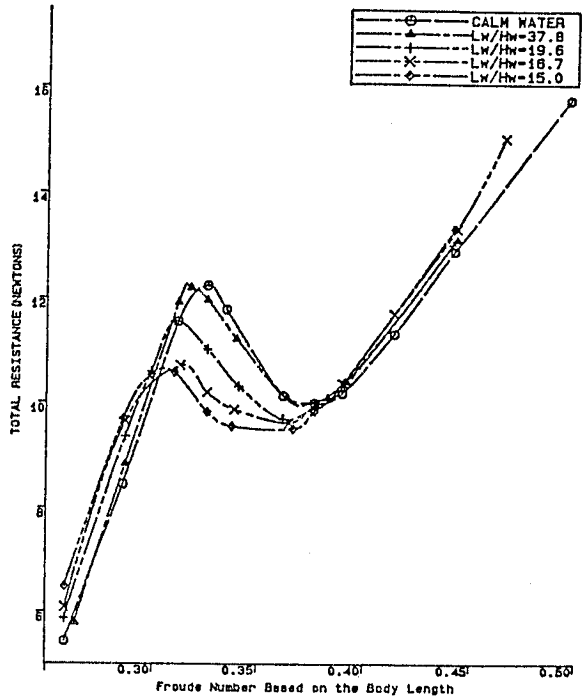
Added resistance coefficient vs non dimensional wave frequency of encounter for SWATH1-C8 at Fn=0.52

Fig.4

DISCUSSION

Raven: Looking at your resistance curves, I do not see a negative added resistance in particular, but a uniform Froude-number shift. This makes me think that the key to this problem is in the wave resistance. Perhaps this could be explored by computing the wave resistance in a quasi-steady manner for a sequence of attitudes that the ship assumes while pitching and heaving. It occurs to me that the negative added resistance would not be found if the resistance curve was monotonically increasing, as it is for most ordinary vessels.

Chun: It is true that negative added resistance did not occur for the SWATH3 model, where the resistance curve increases monotonically (see reference 2). However, from the adjacent figure, which I showed in the discussion (and also Fig. 6 in reference 1), it is clearly not just a uniform Froude-number shift, but also a resistance decrease over the speed range; it is as if the curve is moved down as well as left.



SWATH1 Model-C5 Total Resistance as a Function of Froude Number (Wave Frequency=1.02Hz, Lw/Lb=1.0)

Grue: For 2-D submerged bodies, we have observed that negative added resistance may occur for $\tau > \frac{1}{4}$ and large Froude number. We have found that this is due to one of the scattered wave components, which, in the case of negative added resistance, is predominant [1]. What do you think is the reason for the appearance of negative added resistance in your experiments? If it has something to do with the scattered waves, which part of the wave system is predominant?

Chun: As our geometry is very complicated, it would not be easy to determine the cause from the scattered waves, as in a simple 2-D geometry. We used a 3-D panel method (diffraction theory) and computed forces using a near-field direct pressure integration. From the final formula for the mean second-order force, equation (11), it can be partially explained (but not fully at present). Unlike for monohulls, the contribution due to the wave elevation (first term on right-hand side of (11)) is remarkably small for SWATH models. Coupled with other components, in particular the fourth term on the right-hand side of (11), near-zero added resistance has been observed (see Fig. 3).

Wu: You stated that the total resistance can decrease by up to 24% of the calm-water resistance. How much of this can be attributed to the change in the wetted surface, due to the wave elevation, trim and sinkage?

Chun: At present, we do not know. In normal circumstances, it is known that a small fraction of the total resistance can be caused by the wave elevation, trim and sinkage. However, it is very hard to accept that these factors could explain a reduction of 24% .

Reference

[1] J. Grue & E. Palm, 'Wave radiation and wave diffraction from a submerged body in a uniform current', *J. Fluid Mech.* **151** (1985) 257–278.